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Stereoscopic Versus Orthogonal View Displays for Performance of a Remote Manipulation Task

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ABSTRACT

Within the limited research literature on the topic, there is considerable controversy over the usefulness of stereoscopic TV displays for performing remote manipulation tasks. Some investigators argue that a second video channel might just as well be allocated to a camera with an appropriately separated view of the worksite - an "orthogonal" view to that of the first camera. Other researchers argue that even though operators tend to express strong subjective preferences for stereoscopic displays, these displays often do not provide objective performance advantages. In this experiment we required a group of relatively inexperienced manipulator operators to perform a complex and difficult line threading task remotely and varied the visual displays available to the operators while performing this task. For each video display condition tested, the operator sat in a centered position facing two CRT's, each providing a separate view of the remote task site. Three combinations of video display types were tested: 1) monoscopic view plus orthogonal view, 2) stereoscopic view plus orthogonal view, and 3) stereoscopic view plus monoscopic view. Total task completion times, manipulative errors, and operator gaze preferences were measured for each combination of display types. Results show a strong and consistent operator viewing preference for stereoscopic displays as well as substantial and statistically significant performance advantages for those display combinations that provided a stereoscopic view over those that provided only monoscopic views.

1. INTRODUCTION

While a growing number of researchers and operational users of remote manipulator systems contend that stereoscopic displays provide consistent and substantial performance advantages over corresponding monoscopic displays for many important real-world applications, others are of the opinion that a second video channel might be just as effectively allocated to a camera with an appropriately offset point of view of the work site, a so-called "orthogonal" view to that of the first camera. Measures of subjective preference between stereoscopic and monoscopic displays of the same remote scene have generally **not** been conducted by simultaneous comparison of carefully matched alternative displays that have been counterbalanced for order of presentation or position of presentation over a series of testing sessions. Previous comparisons between stereoscopic and monoscopic displays have relied almost exclusively on operators' verbal reports of which display they liked best subsequent to testing as the sole dependent measure of display preference. One notable exception that involved the use of objective behavioral observation techniques to measure operator display preferences is a study undertaken by researchers at the Atomic Energy Research Establishment at Harwell in the United Kingdom and briefly reported on in at last year's SPIE conference on stereoscopic displays and applications [1,2]. The Harwell group found that when operators were provided a simultaneous choice between viewing a stereoscopic display and an "orthogonal" monoscopic display while performing a remote pick-and-place manipulation task, operators were observed to show a strong preference for the stereoscopic display as evidenced by which display they were observed viewing while performing the task. In conducting the experiment reported here, we hoped to replicate the Harwell findings with a different, but commensurately challenging remote manipulation task. We used readily observable head aiming behaviors as an objective measure of viewing preference, while at the same time measuring task completion times as well as inadvertant collisions of the manipulator arm with the task board.

In total, six display combinations were presented to each operator over the course of the experiment. These combinations are summarized below in Table 1.

TABLE 1. Six display combinations tested.

LEFT-SIDE DISPLAY POSITION	RIGHT-SIDE DISPLAY POSITION
A) Monoscopic (Camera 1)	Orthogonal (Camera 3)
B) Stereoscopic (Cameras 1&2)	Monoscopic (Camera 1)
C) Stereoscopic (Cameras 1&2)	Orthogonal (Camera 3)
D) Orthogonal (Camera 3)	Monoscopic (Camera 1)
E) Monoscopic (Camera 1)	Stereoscopic (Cameras 1&2)
F) Orthogonal (Camera 3)	Stereoscopic (Cameras 1&2)

The general experimental issues that we sought to address were as follows: 1) for those situations in which a manipulator operator is provided two separate televised views of a remote work site, which combination(s) of displays support(s) efficient performance (i.e., fastest task completion times and fewest undesirable collisions with the taskboard)?, and 2) which display type is preferred - monoscopic, orthogonal monoscopic, or stereoscopic - when a choice must be made between two alternatives?

When the operator is required to perform a task that requires precision alignment in depth and orientation, as was the case for the line threading task selected for this experiment, we would expect display combinations that provide more accurate depth and 3-D orientation information to the operator to support more efficient task performance. Additionally, we would expect that a display from which depth and orientation information could be accurately and more readily interpreted would be viewed during a greater proportion of total task time than an alternate display. Thus, we hypothesized the following outcomes, given the range of display combinations that were tested:

1) a stereoscopic display would be clearly superior to a "simple" monoscopic display when that display is identical to one of the two viewpoints comprising the stereoscopic display, because no additional depth or orientation information is provided by such a monoscopic display. That is, it is redundant to the stereoscopic display. With reference to Table 1, combinations B,C,E, and F which include a stereoscopic display should provide superior performance over combinations A and D which do not include a stereoscopic display.
2) a stereoscopic display would be preferred when directly pitted against an orthogonal monoscopic display, because depth and orientation information is less ambiguous and sensitive to viewpoint [1-3] than it is for the orthogonal display. However, since the orthogonal display would provide useful depth and orientation information for some limited set of total task, we would expect the observed superiority of the stereoscopic display to be somewhat less pronounced than in hypothesized outcome 1, above. In more specific terms, we would expect combinations C and F to be preferred to B and E.
3) Since both provide ambiguous 2-D representations of the complex 3-D task, little difference in viewing preference would be expected between the monoscopic display and orthogonal monoscopic display (i.e., between the two displays used in combinations A and D).
4) Given the close contiguity of the two display screens used in this experiment, we would expect little or no effect for side of presentation of a particular display type, though we do include it as a counterbalanced factor in the experimental design since spatial compatibility of control inputs and displays has clearly been shown to exert an influence on performance.

2. METHODS

2.1 Operators

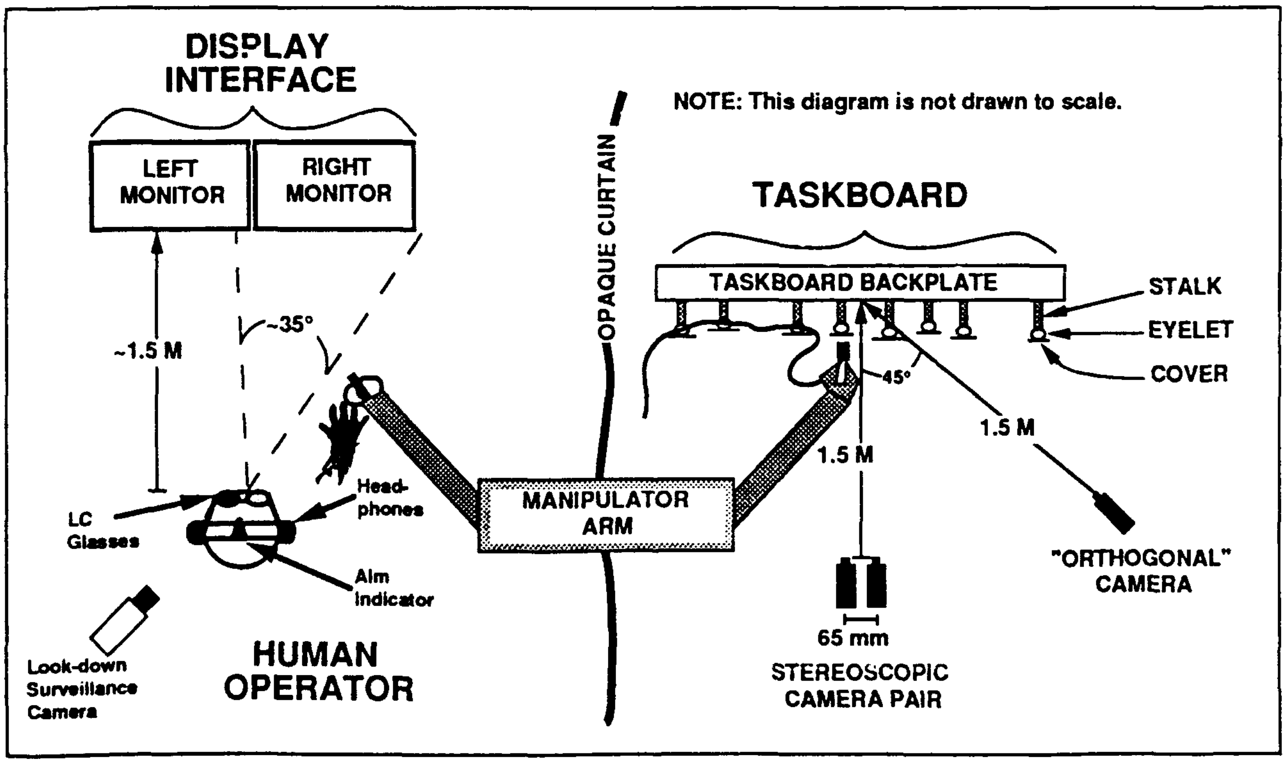
Six experimental operators were tested. All were practiced (i.e., familiar with both the manipulator and the line threading task under direct viewing conditions, though **not** practiced with the specific display configurations used in the experiment). Amount of experience using the manipulator (a CRL Model G master-slave unit) prior to commencement of data collection varied widely among operators. One operator had no more than two hours prior experience using the manipulator, three operators had from 6 to 10 hours prior experience, and the remaining 2 operators each had in excess of 40 hours prior experience. All operators were screened for normal visual acuity and stereoacuity using a battery of standardized vision tests [4] and random dot stereograms. With the exception of one individual, operators were uninformed as to the purpose of the experiment, most particularly to the fact that their viewing preferences were a major subject of interest in the experiment. Fortunately, a comparison of data collected from the one "informed" operator with data collected from the other "uninformed" operators did not

suggest any substantial deviations, so his data was included in the final analyses presented below. All operators participated in the study during normal working hours and none were paid any amount over and above their normal hourly wages for participating.

2.2 Display Interface

A side-by-side pair of 48 cm (19 inch) diagonal black and white TV monitors (Panasonic Model WV5490) provided the operator's only views of the task since a direct view of the taskboard was completely blocked by an opaque curtain. The monitors were centered approximately 1.5 meters in front of the operator, in the arrangement diagrammed below in Figure 1. A 60Hz field sequential technique that provided a 30 Hz monocular alteration rate was used for stereoscopic display [5]. Brightness and contrast levels of all three display types tested (i.e., monoscopic, orthogonal monoscopic, and stereoscopic) were equalized and held constant throughout the entire experiment. Under all test conditions, even those **not** involving use of a stereoscopic display (i.e., A and D in Table 1), operators wore a pair of light shutter glasses for stereo channel separation. These glasses restricted the operator's binocular field of view to a sector approximately 35° horizontal by 15° vertical. Consequently, as is diagrammed in Figure 1, the operator was not able to center his view of one display screen while simultaneously viewing the other screen. Thus, he was forced to use easily observable panning head movements rather than eye movements to look from one display to the other. In addition to the shutter glasses, the operator wore a lightweight set of stereo headphones through which broadband, "pink" noise of constant average intensity was played. This had the effect of masking any audio cues that an operator might use in performing the threading task. Overall brightness of the displays and the ambient lighting in the operator's control station area were held low to minimize the sensation of flicker experienced with 60Hz field sequential stereo display systems used at higher light levels. Magnification for all three display types was matched at a close approximation of 0.7.

Figure 1. Top-view Diagram of Laboratory Layout Used in This Experiment.



2.3 Camera Configuration

A miniature pair of high-quality, black and white video cameras (Pulnix Model TM-540) comprised the stereo camera head. An interaxial separation of 65 mm was used. Cameras were converged by the simple "toe-in" method to a point corresponding to the center of the circular-shaped taskboard, some 1.5 meters in front of the camera pair. As can be seen in Figure 1, the orthogonal monoscopic camera was also positioned 1.5 meters from taskboard center but it was offset from the stereo camera head by 45° relative to the reference taskboard orientation. In setting up all three cameras, care was taken to maintain constant position, focus, aperture setting,

and convergence throughout the entire experiment. Special care was given to the problem of eliminating vertical disparities in stereoscopic images, though this was not entirely possible given the camera convergence technique that was employed[6].

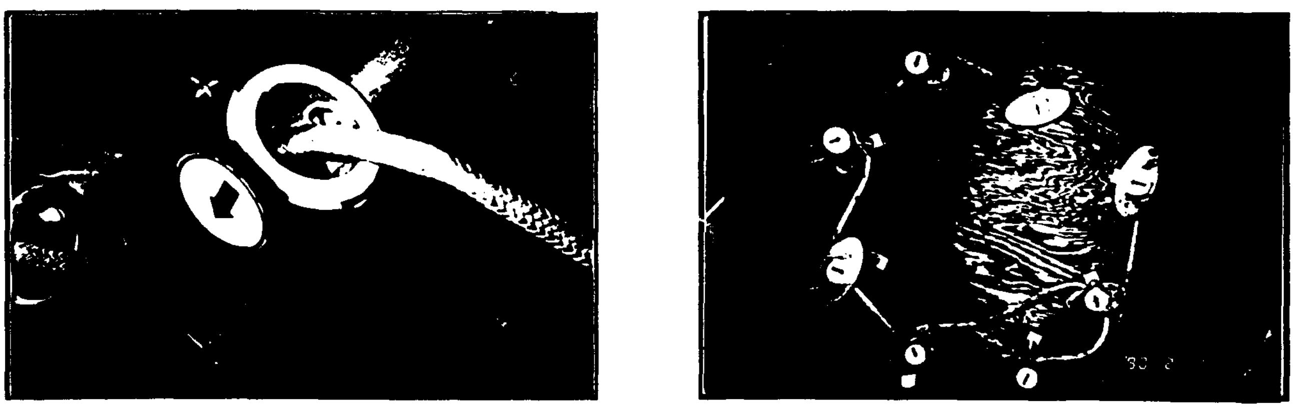
2.4 The Line Feeder Task

The manipulative task was a complex one that involved threading a line through a predesignated series of 8 obscured eyelets that were arranged in varying depths and orientations on a flat circular taskboard backplate. (See Figure 2). A graduated series of "stalks" of varying lengths (i.e, 8.9, 10.2, 11.4, 12.7, 15.2, 16.5, 17.8, 19, and 20.3 cm) offset the eyelets to varying depths from the taskboard backplate. All eyelets were identical, consisting of a 2.5 cm long, hollow ring with an inner diameter of 4.5 cm through which the operator threaded a 3.2 cm rubber coated cylinder with an attached line (i.e., 1 cm or 3/8 inch diameter, braided nylon rope). Thus, the physical tolerance for threading the line was held constant for all 8 eyelets. Each eyelet contained a small IR emitter/receiver circuit for automated recording of the time required for line threading. In the taskboard area of the test room high intensity diffuse lighting from multiple light sources was used to reduce the usefulness of shadow cues produced when the manipulator and line approached any part of the taskboard [see 7, page 23 for further details]. In order to eliminate, or at least minimize, the usefulness of the visual cue of relative size of eyelets, eyelet covers were used. As stated earlier, these obscured an operator's televised view of the eyelet. Eyelet covers were coated with black flocked paper to reduce the effectiveness of shadow cues on approach, and attached arrows signalled the direction in which the line was to be threaded. They were ellipsoidal in shape and were varied in size so that their relative size in the displays was not a reliable cue to depth of the eyelet they obscured. Covers were attached to eyelets with strips of magnetic material. If an eyelet was not touched or otherwise disturbed by the manipulator or the line, it remained attached to the eyelet. However, when physically disturbed during the process of line threading, it would detach and fall to the floor. Operators were instructed to avoid detaching eyelet covers and used their detachment as a rough index of inadvertant collisions or disturbance of the taskboard during the process of line threading. To further complicate the task for the operator and force him to rely on visual feedback provided through the video display interface, we changed the orientation of the taskboard on a trial-by-trial basis in quasi-random fashion.

Figure 2. Views of the Line Threading Taskboard Used in this Experiment.

Close-up view of a single eyelet with attached eyelet cover

Frontal view of taskboard. Note the line with rubber coated cylinder at its end



2.5 Measurement of Gaze Preference

As illustrated in Figure 1, a video camera was positioned unobtrusively above and behind the operator during testing. Unbeknownst to all but one of the operators, this camera provided a video record that could subsequently be used to determine which display the operator viewed while performing the manipulation task. As an aid to the scorer of the video recording, a small white aim indicator was attached to the crown of the set of headphones worn by the operator. This aim indicator provided an unambiguous indication of the direction in which the operator's head was pointed at any given instant during testing. To further aid the scorer, identifying text information was overlayed in the video that uniquely identified each trial for each operator on each day of testing.

Additionally, a video screen splitter was used to continuously log, in the same video recording, a view of the taskboard for verification of collision errors. While scoring the video records, the scorer was unaware of the particular viewing conditions being tested during a particular session.

2.6 Testing Procedure

Each of the 6 operators was tested during 6 separate testing sessions for an experiment total of 36 sessions. Order of presentation of the 6 display configurations listed in Table 1 was counterbalanced across the 6 operators to minimize any systematic effects on results. Each session required approximately one hour to complete. During each session an operator was required to perform 12 discrete threading trials. Each trial consisted of threading the line through a predesignated series of 8 eyelets. Trial times were recorded automatically by a controlling computer. Operators were instructed to emphasize precision of operation by minimizing inadvertant collisions with the taskboard that would result in detaching eyelet covers. Prior to each trial, the taskboard was moved to a different orientation relative to the cameras and manipulator in the manner previously used in our laboratory [8]. In this way, orientation of the taskboard was randomized on a trial by trial basis, forcing the operated to rely more heavily on immediate visual cues rather than on learned position and orientation of the taskboard over an extended series of repetitive trials. The experimenter counted, recorded, and replaced any detached eyelet covers at the conclusion of each trial. Following each trial the operator was informed of total trial time and number of eyelet covers detached during that trial.

3. RESULTS

3.1 Task Completion Times and Inadvertant Collisions

A three-way repeated measures analysis of variance (ANOVA) was run on Total Task Completion Times with Display Combination, Position of Display, and Trial Repetitions serving as independent factors in the analysis Of the three factors analysed for, only Display Combination was found to exert a significant effect on Task Completion Times [omnibus F-value = 14.6, df = 2, Greenhouse-Geisser (G-G) corrected $p < .02$]. No interactive effects in the analysis were found to be statistically significant. The effects of Display Combination on Task Completion Times in seconds are graphed below in Figure 3. As inspection of Figure 3 reveals, there was an approximate 26% reduction in average Task Completion Time for the Stereo-Ortho display combination versus the Ortho-Mono combination, and this mean difference was statistically significant [$F = 19.4$, df = 1, G-G corrected $p < .02$]. Additionally, there was an approximate 29% reduction in average Task Completion Time for the Stereo-Mono combination versus the Ortho-Mono combination. This mean difference was also found to be statistically significant [$F = 24.14$, df = 1, G-G corrected $p < .01$].

Figure 3. Effects of Display Combination on Line Threading Task Completion Times.

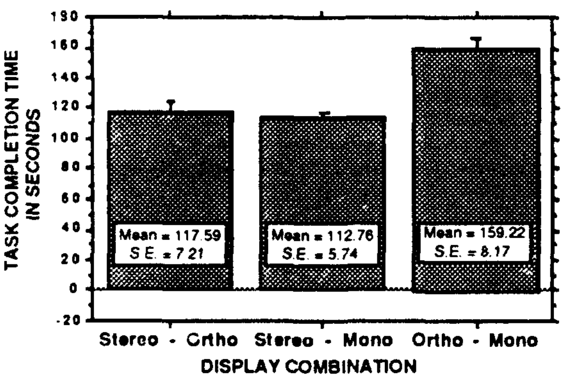
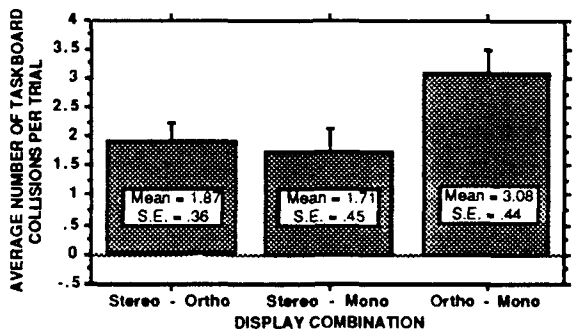


Figure 4. Effects of Display Combination on Inadvertant Collisions with the Line Feeder Taskboard.



NOTE: The error bars graphed in these and subsequent figures represent standard errors (S.E.). Number of trials averaged for each value plotted in Figures 3 and 4 was 96 (i.e., n_obs = 96).

A similar analysis of variance was run on Inadvertant Collision Errors. Like the analysis of Task Completion Times, this analysis revealed that only the Display Combination effect significantly influenced error rates. The

effects of Display Combination on errors (actually, average number of eyelet covers downed per trial) are graphed above in Figure 4. Inspection of Figure 4 reveals that there was an approximate 39% reduction in error rate for the Stereo-Ortho display combination versus the Ortho-Mono combination [$F = 9.22$, df = 1, G-G corrected $p < .02$]. There was an approximate 44% reduction in average error rates for the Stereo-Mono combination versus the Ortho-Mono combination [$F = 11.93$, df = 1, G-G corrected $p < .01$]. No significant difference was found between the Stereo-Mono and Stereo-Ortho combinations.

3.2 Gaze Preferences

A chi-square test was run to test the hypothesis that when given a choice between a stereoscopic display and one of the two monoscopic display types that were presented (i.e., configurations B,C,E, and F in Table 1), operators would be equally likely to view either stereoscopic or monoscopic displays. If the hypothesis were true, when averaged over the series of sessions run, this would result in viewing times approximating 50% for both stereoscopic and monoscopicdisplay types used within a session. Results of the analysis [chi-square = 232.65, df = 5, $p < .001$] showed a very strong, consistent and statistically significant preference for viewing stereoscopic displays over either of the monoscopic display types tested.

A three-factor, repeated-measures ANOVA was run on stereoscopic display preference scores (proportion of time spent viewing the stereoscopic display during a trial) with Display Combination (Stereo-Mono or Stereo-Ortho), Position of the Display (Left or Right), and Trial Number serving as main effects in the analysis. None of the simple or interactive effects in the experiment were statistically significant. However, an interesting trend was found for the Display Combination effect and this is plotted below in Figure 5. Inspecting Figure 5, one can see the high proportion of time that operators viewed the stereoscopic display when either the simple monoscopic (98.3% stereo preference) or the orthogonal monoscopic display (92.1% stereo preference) vied for their attention. One can also see a slight, statistically non-significant ($p = .096$) tendency for operators to spend approximately 6% more of their time viewing the orthogonal display when it competes for their attention than they spend viewing the monoscopic display when it competes.

A chi-square test was run to test the hypothesis that the two monoscopic display types were equally preferred in those sessions where they vied for the operator's attention (i.e., combinations A and D). The attentive reader will recall that we did not expect to find a difference in gaze preference for this viewing situation, since both views provided similar information regarding the relative depth and orientation of the eyelets that had to be threaded. It should be noted, however, that the orthogonal view did enable the operator to see around the eyelet covers in many instances and this may have well proven advantageous. In view of this, the results of the chi-square test were surprising because they revealed a substantial preference for the simple monoscopic view over the orthogonal view [chi-square = 164.61, df = 1, $p < .01$]. This preference for simple monoscopic over the orthogonal monoscopic view is graphed in Figure 6 which also illustrates that there was no significant effect for the position in which the monoscopic display types were presented.

Figure 5. Stereoscopic Display Viewing Preference as a Function of Display Configuration. n_obs = 120.

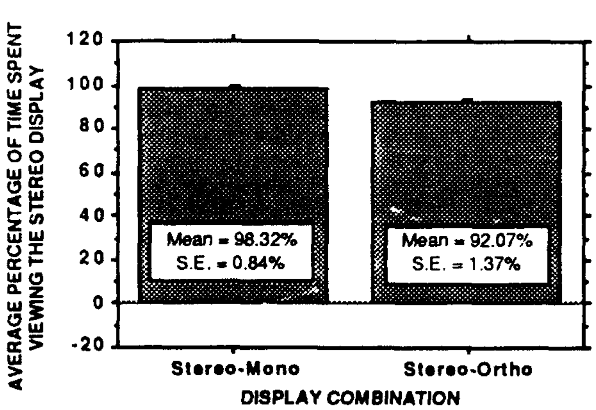
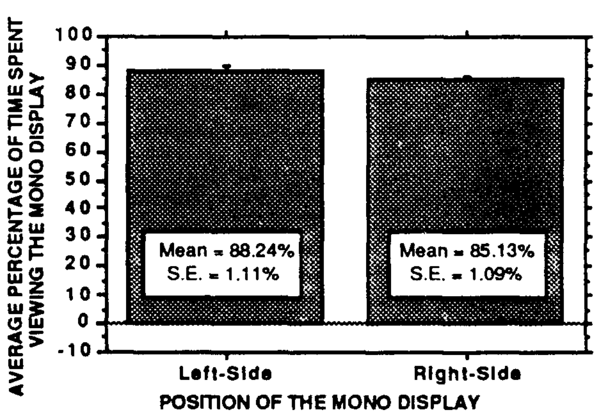


Figure 6. Display Preference for the Simple Monoscopic Display Over an Orthogonal View as a Function of Display Position. n_obs = 72.



4. DISCUSSION

Overall, the pattern of results found in this experiment strongly parallel the previously published findings of the AERE - Harwell research group in the UK [1,2]. While their previous experiment showed an overall ~12% task completion time advantage for a stereoscopic display over a monoscopic display, the present study showed even more pronounced effects of ~26% and ~29% advantages in task completion times over orthogonal and simple monoscopic displays, respectively. The discrepancy between the two remote manipulators and tasks used in the previous experiment and this experiment might well account for this sizeable discrepancy between the observed stereoscopic task time advantages. To elaborate, the manipulator used in the earlier experiment may have imposed greater limitations on performance times than the direct-banded, "through-the-wall", master-slave device with force feedback that was used in this experiment. In addition, the line threading task used here probably demanded more precision for successful completion than the "toast rack" task employed in the earlier experiment. Moreover, to a large extent, the visual components of the task required of operators in this experiment were designed to enhance the value of stereoscopic cues by reducing the availability of other cues to depth and orientation (e.g., relative size, well-defined shadows). This experiment also incorporated a simple measure of error, of inadvertant collision with the taskboard, in the form of the detachable eyelet covers. The error data collected here also demonstrated a strong advantage for the use of stereoscopic displays over simple monoscopic displays [39% advantage] as well as orthogonal monoscopic displays [44% advantage]. Most striking was the concordance between the previous experiment and this experiment with respect to gaze preferences. Whereas, Dumbreck, et al. [2, p. 200] observed an overall stereoscopic display gaze preference of 94.6%, we observed an overall 95.2% preference. Taken together, the results reported here offer strong support to the general conclusion that stereoscopic displays are advantageous for remote performance of complex, three-dimensional manipulation tasks. In this experiment, when compared to both simple and orthogonal monoscopic displays, a stereoscopic display significantly and substantially lowered times required for overall task completion, improved precision of operations, reduced inadvertant collisions with the taskboard, and was objectively observed to be very strongly preferred when operators were given an immediate choice between viewing either a stereoscopic display or a monoscopic one.

Our initial hypothesis that position of the displays used in this experiment would exert little effect on the outcomes of the performance measures was supported by the results. No significant main or interective effects were found for this Display Position effect in any of the analyses conducted. This conclusion must, however, be qualified by two provisions. First, the displays used for this experiment presented only a rather modest field of view and were centered directly in front of the operator at eye level. Secondly, the video displays were also distanced just outside the zone of motion for the operator and manipulator master, and therefore did not physically constrain the operator's physical control inputs. Both these provisions are important considerations in designing any control interface for remote manipulation.

Our initial hypothesis of no significant difference between the simple and orthogonal monoscopic views was not supported by the results of this experiment. A strong, consistent preference was found for the "simple" monoscopic view over the orthogonal monoscopic view. Exactly why this result occurred cannot be determined from the results of this study, but may have been due to a closer, or more "natural", spatial correspondence between control inputs and movement feedback provided to the operator by the video display [9]. Because the operator's viewpoint (i.e., distance, angle of regard, field of view relative to the display surfaces) corresponded very closely to that of the camera providing the "simple" monoscopic view of the taskboard, the visual feedback provided the operator was very similar to that available under normal, direct viewing conditions. In other words, the operator's visual-motor frame of reference remained largely unchanged with only minor adjustments needing to be made for distortions introduced by video viewing with a fixed position camera. For example, under the simple monoscopic viewing condition, when the operator moved the manipulator grip to the left 5 °, the image of the manipulator gripper in the display moved left by an amount approximating and directly proportional to 5°. Using the simple monoscopic view, when the operator moved the manipulator grip in depth, closer to or further away from the taskboard and its eyelets, the relative size of the gripper changed accordingly in his view of the scene, with some vertical movement but little or no lateral movement on the display screen. When an orthogonal monoscopic view was provided, however, the operator was required to perform a shift in his visual-motor frame of reference to perform the task. A manipulator grip movement to the left 5° was seen as a much smaller angular shift to the left in the orthogonal view. More importantly, though, a movement of the arm in depth toward or away from the taskboard resulted in a sizeable angular shift to the left or right on the display screen. The added mental burden of transforming one's visual-motor frame of reference may have discouraged operators from using this display whenever it competed with the simple monoscopic view. An alternate explanation for the results holds that some

component of the observed preference for the simple monoscopic display may have been the result of operant conditioning. Since the viewpoint provided by the simple monoscopic display was very similar to (in fact identical to one-half of) the highly preferred stereoscopic display. Over the course of testing, operators would build up greater familiarity with that viewpoint and perhaps come to associate it with more rewarding performance. A definitive answer to these speculations is beyond the scope of this experiment and this brief report. Perhaps more work will be performed in the future to clarify these issues and gain a more precise and satisfying understanding of the powerful effects of viewpoint and visual-motor correspondance on remote manipulation and remote operations in general.

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